2. Landfill Gas Modeling

Chapter Overview

Landfill gas (LFG) modeling is the practice of forecasting gas generation and recovery based on past and future waste disposal histories and estimates of collection system efficiency. LFG modeling is an important step in the project development process, because it provides an estimate of the amount of recoverable methane that will be available over time to fuel an LFG energy project.

LFG modeling is performed for regulatory and non-regulatory purposes. *Regulatory applications* of LFG models for U.S. landfills are conducted to estimate emissions of LFG and its constituents, including non-methane organic compounds (NMOCs). These emissions estimates establish the requirements for gas collection and control system installation and operation. The modeler inputs landfill-specific waste disposal estimates but uses values for input variables (e.g., the methane generation rate) as determined by applicable regulations.

Non-regulatory applications of LFG models typically include any of the following:

- Evaluating LFG energy project feasibility
- Determining gas collection and control system design requirements
- Performing due diligence evaluations of potential or actual project performance

This chapter covers non-regulatory LFG modeling applications only. EPA does not intend for the material presented in this handbook to supersede or replace required procedures for preparing LFG models for regulatory purposes. Federal regulations such as the New Source Performance Standards (NSPS) require modeling to determine rule applicability and compliance. For regulatory applications, the modeler must use the specific procedures, default vales, and test methods prescribed in the rule. Refer to the appropriate regulations (e.g., the NSPS [40 CFR part 60 subpart WWW] and related documentation) for details.

2.1 Introduction to LandGEM

The most widely used LFG model is EPA's Landfill Gas Emissions Model (LandGEM). LandGEM is the industry standard model for regulatory and non-regulatory applications in the United States. The latest version of LandGEM (v. 3.02) was released in May 2005. This section provides an introduction to LandGEM and the first order decay equation and variables employed by the model.

The First-Order Decay Equation

LandGEM is a first order decay model. First order decay models assume that landfill methane generation is at its peak shortly after initial waste placement (after a short time lag during which anaerobic conditions are established in the landfill). They also assume that landfill methane generation then decreases exponentially (i.e., first order decay) as the organic material in the waste decreases as it is degraded by bacteria in the landfill.

LandGEM assumes that landfill methane generation can be projected using the following first order exponential equation:

$$Q_{CH4} = \sum_{i=1}^{n} \sum_{j=0.1}^{1} k\, L_o\, (M_i/10)\, (e^{-kt_{ij}})$$

Where:

Q_{CH4} = estimated methane generation flow rate (in cubic meters [m^3] per year or average cubic feet per minute [cfm])

i = 1-year time increment

n = (year of the calculation) – (initial year of waste acceptance)

j = 0.1-year time increment

k = methane generation rate (1/year)

L_o = potential methane generation capacity (m^3 per megagram [Mg] or cubic feet per ton)

M_i = mass of solid waste disposed in the i^{th} year (Mg or ton)

t_{ij} = age of the j^{th} section of waste mass disposed in the i^{th} year (decimal years)

LandGEM calculates methane generation using the first order decay equation shown above, and it calculates LFG generation by dividing methane generation by the estimated percent methane. The default methane content is 50 percent, which is both the industry standard value and LMOP's recommended default value.

Model Inputs

Of the several variables in the first order decay equation used by LandGEM, only three (M_i, L_0, and k) require user inputs. The user assigns these variables in a "USER INPUTS" worksheet in LandGEM. The following sections describe the three variables and their effects on estimated LFG generation.

Annual Waste Disposal Rates (M_i). Estimated waste disposal rates are the primary determinant of LFG generation in any first order decay-based model, including LandGEM. LandGEM does not adjust annual waste disposal estimates to account for waste composition. Adjustments to account for waste composition are typically handled by adjustments to the L_0 value.

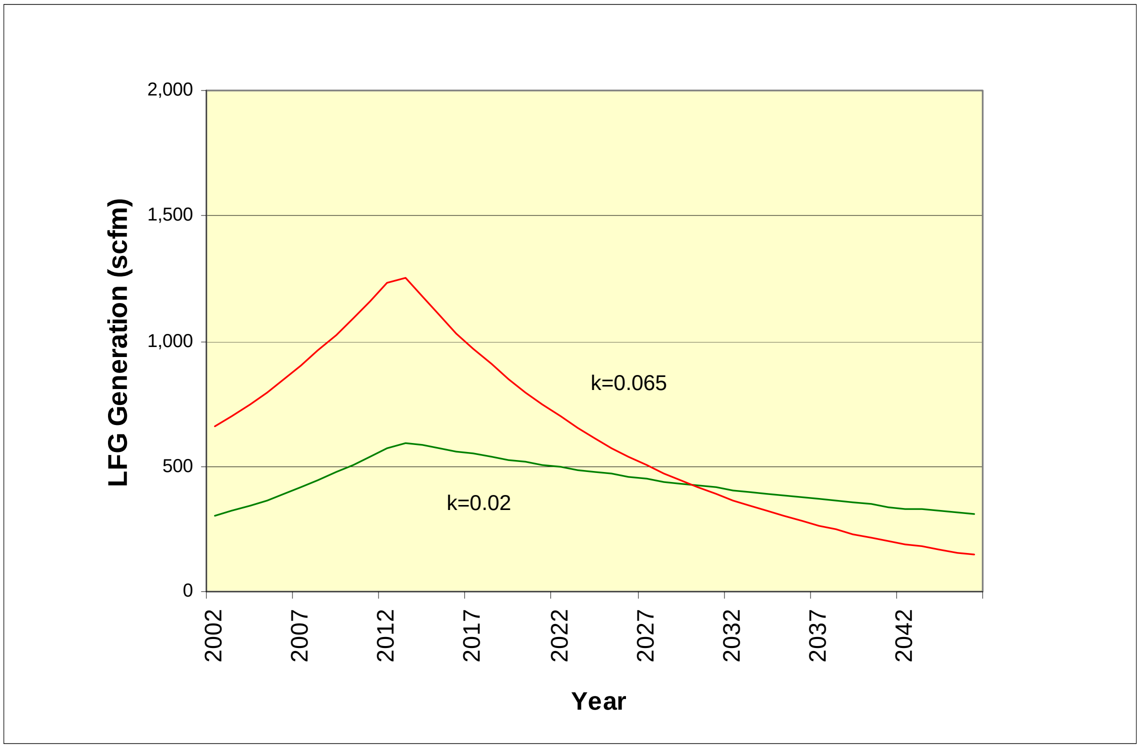
Potential Methane Generation Capacity (L_0). The potential methane generation capacity, or L_0, describes the total amount of methane gas potentially produced by a metric ton of waste as it decays. The values of the theoretical and obtainable L_0 range from 6.2 to 270 cubic meters per metric ton or megagram (m^3/Mg) of waste.[1] Except in dry climates where lack of moisture can limit methane generation, the value for the L_0 depends almost entirely on the type of waste present in the landfill. The higher the organic content of the waste, the higher the value of L_0. Note that the dry

[1] U.S. EPA. 1991. *Air Emissions From Municipal Solid Waste Landfills — Background Information for Proposed Standards and Guidelines.* EPA-450-3-90-011a. p. 3-22.

organic content of the waste determines the L_0 value, not the wet weight measured and recorded at landfill scalehouses, since water does not generate LFG.

Methane Generation Rate Constant (k). The methane generation rate constant, k, describes the rate at which waste placed in a landfill decays and produces LFG. The k value is expressed in units of year^{-1}. At higher values of k, the methane generation at a landfill increases more rapidly (as long as the landfill is still receiving waste), and then declines more quickly after the landfill closes. The value of k is a function of (1) waste moisture content, (2) availability of nutrients for methane-generating bacteria, (3) pH, and (4) temperature. Figure 2-1 shows an example gas curve for a landfill with approximately 2 million tons waste-in-place expected at closure. The potential gas generation was modeled in two scenarios, using identical landfill parameters except that k was varied between a value for arid conditions (0.02 yr^{-1}) and a value for wet conditions (0.065 yr^{-1}). The graph demonstrates the significant difference in gas generation that can occur based on moisture conditions at the site.

Figure 2-1. LFG Generation Variance by k Value



Moisture conditions within a landfill strongly influence k values and reflect the climate at the site as well as the contents of disposed waste and landfill design and operating practices. Waste decay rates and k values are very low at desert sites, tend to be higher at sites in rainier climates, and reach maximum levels under moisture enhanced “bioreactor” conditions. Annual precipitation is often used as a surrogate for waste moisture due to the lack of information on moisture conditions within a landfill. Air temperature can also affect k values, but to a lesser extent. Internal landfill temperatures are relatively independent of outside temperatures and typically remain in the range of approximately 30 to 60 °C (85 to 140 °F) except at shallow, unmanaged landfills in very cold climates (e.g., landfills located in areas above 50 degrees latitude). For such landfills, waste decay rates and k values tend to be lower.

The k value can also be expressed as a half-life, $t_{1/2}$. The half-life is the time required for half of the remaining methane generation potential to be produced (i.e., half of the deposited waste to decay and produce LFG).

Refer to the LandGEM User's Manual for additional details on model use.

Model Outputs

LFG Generation. After the model inputs are selected, the user can turn to the "RESULTS" worksheet in LandGEM to find model outputs. The outputs include annual waste inputs, waste-in-place, and generation of total LFG, methane, carbon dioxide, and NMOCs. LFG and methane generation estimates are the output parameters that are used for non-regulatory LFG predictions. Once the LFG and methane generation is estimated, the collection efficiency must be estimated to determine the expected amount of LFG available for an LFG energy project

2.2 Estimating LFG Gas Recovery

Estimating Collection Efficiency

Collection efficiency is a measure of the gas collection system's ability to capture generated LFG. The LFG generation predicted by the model can be multiplied by the percent collection efficiency to estimate the volume of LFG that can be recovered for flaring or use in an LFG energy project. Although rates of LFG capture can be measured, rates of generation in a landfill cannot be measured; therefore, considerable uncertainty exists regarding actual collection efficiencies achieved at landfills.

To help address the uncertainty surrounding collection efficiencies, EPA has published estimates of reasonable collection efficiencies for U.S. landfills that meet U.S. design standards[2] and that have "comprehensive" gas collection systems. EPA defines a "comprehensive" LFG collection system as a system of vertical wells and/or horizontal collectors providing 100 percent collection system coverage of all areas with waste within one year after the waste is deposited. According to EPA, collection efficiencies at such landfills typically range from 60 to 85 percent, with an average of 75 percent most commonly assumed.[3] Most landfills, particularly those that are still receiving wastes, will have less than 100 percent collection system coverage. In such cases, LFG modelers commonly use a "coverage factor" to adjust the estimated collection efficiency. The coverage factor adjustment is applied by multiplying the collection efficiency by the estimated percentage of the fill areas with

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[2] Landfills that meet or exceed the requirements in the 40 CFR Parts 257 and 258 RCRA Subtitle D Criteria.

[3] U.S. EPA. 1998. Volume 1, Chapter 2, Section 2.4: Municipal Solid Waste Landfills. In *AP42 Compilation of Air Pollutant Emission Factors.* Fifth Edition. p. 2.4-6. http://www.epa.gov/ttn/chief/ap42/ch02/final/c02s04.pdf.

wells. This adjustment also should be applied to areas where wells are not fully functioning or are watered in.

Collection efficiency estimates for sites with an operating gas collection and control system are typically based on information regarding current or recent conditions. Historical and future collection efficiency estimates can be made based on current conditions or other information regarding historical and planned collection system installations/expansions. Collection efficiency usually increases after site closure when disposal operations stop interfering with LFG system operations and a final cover is installed. Sites without collection systems installed are typically assumed to be planning to install a comprehensive system, unless there is site-specific information to suggest a different value.

Estimating LFG Recovery

The final step in the modeling process is to calculate LFG recovery based on LandGEM projections of LFG generation and the modeler's estimated collection efficiency. This step is done outside LandGEM and can be accomplished by setting up a spreadsheet that provides the LFG generation estimates, the collection efficiency estimates, and LFG recovery estimates (product of generation and percent efficiency). Table 2-1 shows a recommended format for displaying results and the waste disposal estimates on which they are based.

Table 2-1. LFG Generation and Recovery Projections

Year	Disposal Rate	Waste-in-Place	LFG Generation		Collection Efficiency	LFG Recovery	
	(tons/year)	(tons)	(scfm)	(m^3/hr)	(%)	(scfm)	(m^3/hr)
Year 1							
Year 2							
Year 3							
Year X (final year modeled)							

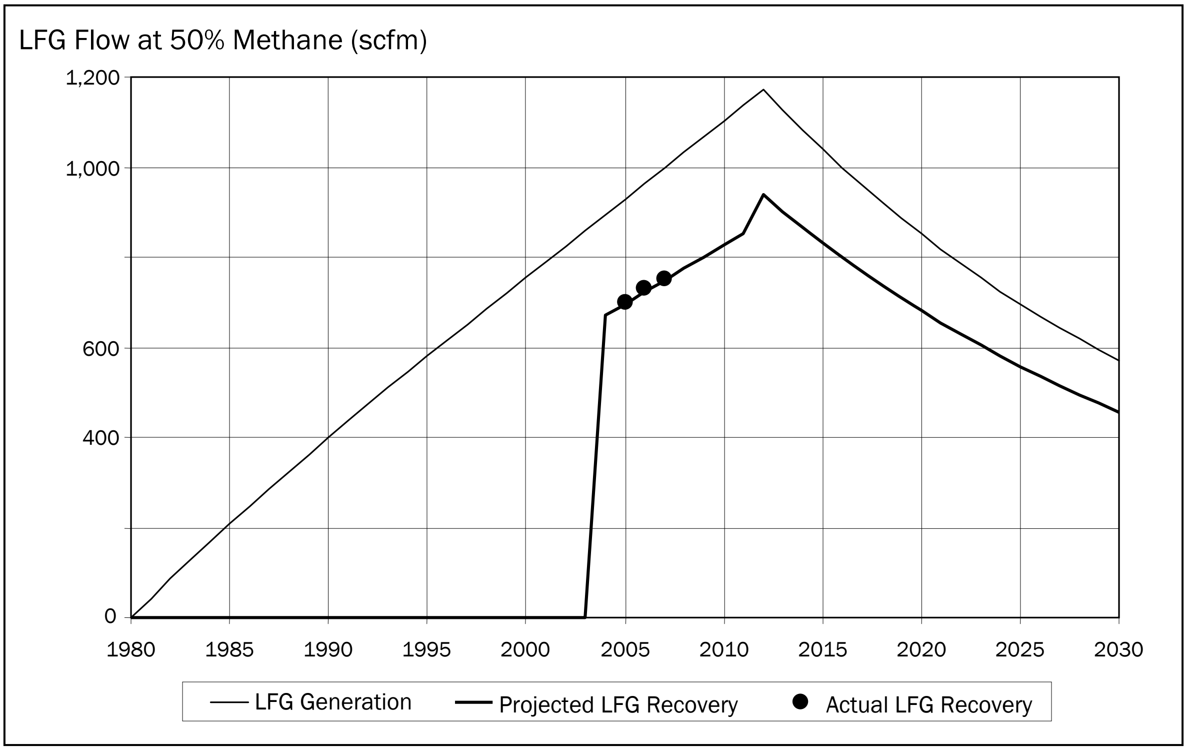
scfm: standard cubic feet per minute

The LFG recovery projections can also be displayed graphically. Both LFG generation and recovery can be displayed as line graphs in an "X-Y scatter" graph, showing LFG flow at 50 percent methane (Y-axis) in each year since the landfill opened (X-axis). For sites with operating collection systems and recovery data, the graph can be used to display actual recovery as dots. The graph can be used to compare projected to actual recovery for model calibration, which involves adjusting model k and L_0 values so that the projected LFG recovery rates closely match actual recovery.[4] Figure 2-2 shows a

[4] This handbook does not cover procedures for model calibration. LMOP recommends seeking the help of an experienced professional LFG modeler to perform model calibration.

sample model output graph for a landfill that opened in 1980, installed a gas collection system in 2003,[5] and will stop accepting waste at the end of 2011.

Figure 2-2. LFG Generation and Recovery Rates



Special Considerations for Bioreactor and Leachate Recirculation Landfills

In recent years, certain landfills have been designed and managed to deliberately introduce liquids into the waste in a controlled manner. This is done in order to speed up the waste decay process and shorten the time period of LFG generation. Landfills that achieve 40 percent moisture content in the waste through the controlled introduction of liquids (other than leachate and condensate) are considered "bioreactor" landfills according to EPA air regulations.[6] Landfills that introduce liquids (most commonly leachate and condensate) but achieve waste moisture contents less than 40 percent are considered "leachate recirculation" landfills. Bioreactor studies conducted by EPA's Office of Research and Development provide additional information.

The introduction of liquids into the landfill causes significant increases in waste decay rates and k values. This increase in k will cause gas generation to increase more rapidly while the landfill is receiving waste and decrease more rapidly once disposal stops, but will not change total LFG generation over the long term. Because only the rate of LFG generation is affected, L_0 values should theoretically be unaffected by liquids introduction. LandGEM provides a default k value of 0.7 for modeling bioreactor landfills (i.e., the "inventory wet" value). LMOP, however, recommends assigning

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[5] LFG recovery starts at known or projected date of the installation of the gas collection and control system.

[6] "Bioreactor" is defined in the municipal solid waste landfill National Emission Standards for Hazardous Air Pollutants, 40 CFR part 63, subpart AAAA.

a k value of 0.3 for bioreactors based on a University of Florida study completed shortly after LandGEM was released. No single k value is recommended or appropriate for leachate recirculation landfills because the impact of leachate recirculation on LFG generation varies depending on the amount of liquids added and the moisture content of waste achieved.

Sometimes, only a portion of a landfill's total site is designed and operated as a bioreactor or leachate recirculation landfill. In such cases, the bioreactor or leachate recirculation portion should be modeled separately from the remainder of the site, using waste disposal inputs for these areas only.

2.3 Model Limitations

Various factors can affect the accuracy of LFG recovery projections:

- *Limited or poor quality disposal data*. Significant model error can be introduced if good disposal data are not available.
- *Atypical waste composition*. Waste composition data are often not available to determine if unusual waste composition is a cause of model inaccuracy.
- *Poor quality flow data and/or inaccurate estimates of collection efficiency used for model calibration.* Model calibration requires both accurate estimates of collection efficiency and good quality flow data that is representative of long-term average recovery.
- *Inaccurate assumptions*. Inaccurate assumptions about variables such as future disposal rates, site closure dates, wellfield buildout, expansion schedules, or collection efficiencies can result in large errors in predicting future recovery.
- *Limitations due to the structure of LandGEM*. For example, LandGEM cannot accommodate changes in k or L_0 values in the same model run. Changing landfill conditions that cannot be modeled as a result of this limitation include the following:
  - Application of liquids to existing waste
  - Variations in waste composition over time
  - Installation of a geomembrane cover

The LFG modeler should be aware of the potential for model error due to the above-listed factors and use appropriately conservative model inputs to avoid significant overestimation of LFG recovery. Accurate estimates that do not overestimate recoverable methane are critical to the proper design and financial success of LFG energy projects.